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Investigation of Critical Fire Weather Pattern - Case Study

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Abstract: A series of huge wildfires occurred in some regions in Lebanon in mid - October 2019, in which the region witnessed a heat wave with high averages of minimum and maximum temperatures, accompanied with dry weather conditions. This study aims to investigate the weather pattern that dominated over Lebanon for the period (10-18) of October 2019, and to study the weather factors that ignite and spread the fire in several places, focusing on Chouf district, in Mount Lebanon Governorate in which it witnessed the most severe wildfire outbreak, based on ERA5 atmospheric reanalysis data at the surface and upper levels for the period (10-18) of October 2019. It was found that the existence of atmospheric blocking system over the region for many days was the main factor in creating the dry and extremely hot weather, and the ridge outbreak caused the ignition of fire, reinforcing the wildfire intensity and amplifying the fire patches to other regions.

Keywords: Atmospheric blocking, fire weather, heatwave, Lebanon, Mediterranean

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1. Introduction

Forestry fires are a major risk and serious damage to the mankind, environment, and economic conditions around the world, and Mediterranean region is one of the most fire-prone regions. The most important natural causes of forest fires are related to extreme global climatic conditions [1], [2], and there are four major weather elements that produce extreme fire behaviour: high temperatures, low relative humidity, strong surface wind, and unstable air which increases the probability of thunderstorms and strong downdraft winds [3]. The spatial distribution of vegetation, their species and moisture content is another crucial factor in fire severity [4], [5]. Fire Behavior is affected by the nature of the region, in which aatmospheric processes in complex and mountainous terrain result in a variety of phenomena , where there are two main wind types that should be considered for better predicting fire behaviour in mountainous regions: large-scale dynamically driven winds and thermally driven winds [3]. In addition to all those main factors, human activities has its important role in enhancing or suppressing fire activity such as the forest deforestation and land use[6].

The number of fires and the size of the area consumed in recent decades have significantly increased, and the danger of forest fires is predicted to increase, in particular around the Mediterranean due to climate change which will reduce fuel moisture levels making the region drier; furthermore, areas exhibiting low moisture will extend further northwards from the Mediterranean, and the area of high fuel moisture surrounding the Alps in the current climate conditions is predicted to decrease in size, thus adaptation strategies will be crucial to lessening the detrimental impacts of climate change on forest fires and the reductions in biomass, and biodiversity [7], [8].

Depending on the geographical position, phenomenon such as heat waves and extreme dry conditions with large fires and floods may arise in season under pre-existing conditions as a result of blocking[9], in which it has a strong impact on the evolution of weather patterns, and understanding this phenomenon is significant to be able to predict the probability of the occurrence of fire weather and the duration of its lasting.

Blocking is a long standing structure stalled in the mid-troposphere which is often associated with extreme weather events. When blocking starts, the weather pattern is moving from west to east and stops in certain places for several consecutive days and sometimes it extends for a month[10]. Blocking over large areas is most common when a high pressure system is dominated, because it covers a broad area and tends to move slower than a low pressure system, with a lifespan varying from few days to a few weeks, leading to severe and persistent weather anomalies [11].

Blocks often exhibit a large anticyclone anomaly and reverse zonal flow, so that in some part of the blocked region, net easterly winds are seen by disrupting the usual western flow for a long time like a week or longer[12]. Atmospheric blocking, commonly associated with clear skies with increased solar isolation at the surface, adiabatic warming with sinking motion as well the warm air advection, is underlying drivers for heat waves. Two mechanisms of permanent summer heat events are: the persistently blocking of resonant circulation regimes, and the reduced baroclinicty and decreased eddy kinetic energy featured by the boreal summer season [10].

Many studies have focused on atmospheric weather patterns and the heat waves they cause and other extreme weather phenomena, which are one of the indicators of climate change, that increase the likelihood of fires occurrence.

Dong et al. (2018) provided a unique case study in which blocking, drought, heat wave and urban heat island all occur concurrently, concluding that atmospheric blocking is capable of reinforcing droughts, initiating heat waves, and probably amplifying the urban heat island intensity during the (13–17) August 2007 over the US [10]. Woollings et al. (2018) reviewed the state of knowledge regarding blocking under climate change, with the aim of providing an overview for those working in related fields, and they identified several avenues by which blocking can be improved in numerical models, though a fully reliable simulation remains elusive (at least, beyond a few days lead time) [13]. Efe et al. (2019) studied the relationship between atmospheric blocking and temperature anomalies in Turkey between 1977 and 2016 for blocked and non-blocked days, and the analysis included blocking events and how it plays a crucial role on the temporal distribution of the mean seasonal temperature anomaly of all stations[12]. Rodrigues et al. (2019) studied the relationship between the atmospheric conditions in the Iberian Peninsula and fire occurrence on the Spanish mainland, and concluded that fire events can be promoted under specific atmospheric patterns, and they are linked to summer heat waves, and for the mountain regions the fires can be activated in the lee side due to the adiabatic heating taking into account the wind speed and direction[14].

Because of this exacerbation of the rate of fires, many indices were used in prediction the forest fires all over the world such as Fire Weather Index (FWI) [15], normalized difference vegetation index (NDVI) [16] and vegetation health index (VHI)[17], in addition of using GIS techniques [18][19] .

Lebanon, located to the east of the Mediterranean Sea, witnesses forest fires that occurs in the dry hot summers which frequently coincide with high temperatures, wind speed and wind directions. Some researches on Lebanon forest fire has shown that over the period between 1983 and 2003, about 67% of fires occurred due to the high temperatures related to high wind frequencies, while without wind frequency about 24% of fires can occur only at high temperatures[1]. In general, 15% of the areas of Lebanon, especially in Mount Lebanon and North Lebanon, where the density of vegetation is high, are subject to flaring in a "very high" manner, while 34% of the Lebanese land areas are subjected to fires whose risk ranges between medium and high. Often, the season of fires occur and developed in June, and continues until October. Recently, large green areas have been burnt out by fire in Lebanon. The green area was 35% in 1960-1965; the percentage of forest cover in Lebanon in 2006 has decreased to 13% in 2006, where the high summer temperature reduced vegetation's humidity to less than 5%. Under these conditions, a slight flame, burning cigarette or even a match may be enough to start a devastating fire. It is worth remembering that sloping ravines and high temperatures, and the high speed dry easterly wind all contribute to exacerbating the situation[20].

Due to the frequent cases of fires that Lebanon is exposed to, and because of its impact on life, climate and the environment, this research aims to investigate the weather pattern that dominated over Lebanon in the period 10-18 of October 2019, which led to several fires, and to study the weather factors that ignite and spread the fire in several places.

2. Materials and Methods

2.1 Study area

For investigating the weather patterns, the study area includes the whole Mediterranean region (24°W - 60°E, 10°S - 65°N), focusing on the Mount Lebanon region and particularly on Chouf (or Shouf) district (33.69556° N, 35.57917°E) located to the south of Beirut because it was one of the most affected regions in this fire series and in the whole year of 2019 as shown in Figure 1 [21].

Topographically, Lebanon can be divided into four parallel sections from west to east[1]: A flat, narrow coastal strip parallel to the sea rises steeply to Mount Lebanon , along with a narrow fertile plain; The Mount-Lebanon chain, the highest crest of which is just over 3000 m; The Bekaa Valley at a height of around 900 m and 8-10 km wide, and The Anti-Lebanon Mountains chain along the border with Syria, which rises to 2800 m, in the east as shown in Figure 2.

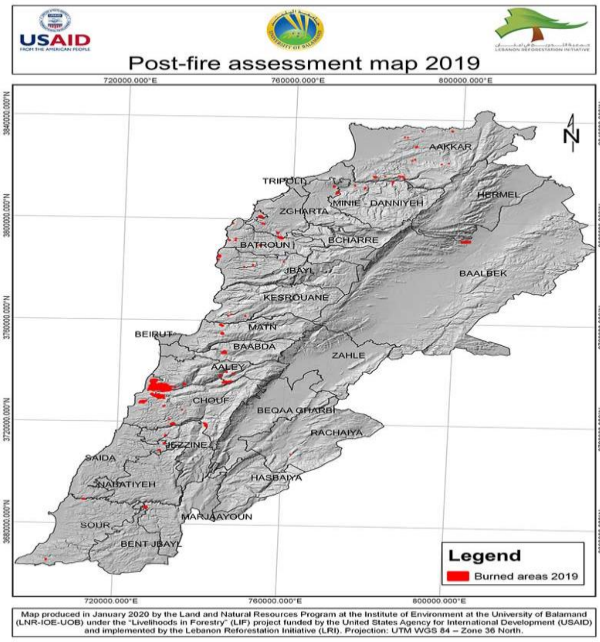


Figure 1. The burned areas (i.e., above 0.1 ha) of 2019 including the disastrous fires of October 2019[21].

The mountain range of Lebanon rises steeply from coast to mountains reaching 3,088 meters above sea level and preserves most forests in Lebanon. About 33 percent is rated as moderate to very high fire threat areas in the national region. Like other Mediterranean countries, fires occur mainly in the dry season and human activity is responsible for the majority of ignitions[23].

The Chouf District is one of the six districts of Mount Lebanon Governorate. extending from the Mediterranean Sea coast westerly to Barouk mountain easterly, and from Damour river northly to El Aouali Markits southerly. It has a typical Mediterranean climate, with a maximum average temperature of 20 °C in August (hot and dry summer) and minimum temperature of 4°C in January (cold and wet winter). It is characterized in having natural reserve of Cedar lies to the west of Mount Lebanon[24].

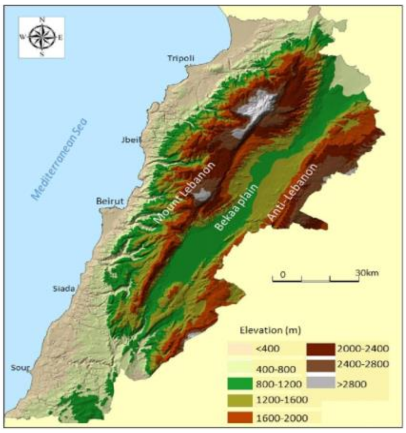


Figure 2. Major topographic units of Lebanon [22]

2.2. Weather Patterns Investigation

As for weather patterns, it is essential to identify the atmospheric weather patterns in the upper levels (500, 700 and 850 hPa) by observing their evolution, domination, and movement using some meteorological parameters including geopotential height, relative vorticity, vertical velocity and relative humidity for different domains covering the Mediterranean region depending on the tested parameters for the period (10-18 October 2019). While testing those parameters, it is important to watch the feedback of the upper pressure systems on the surface by testing surface pressure, surface temperature and dew point at 2m, maximum and minimum temperature at 2m, u and v components of wind and wind gust at 10m, total and convective precipitation, and total cloud cover. Also the total total index was used as an indicator of the probability of occurrence of a thunderstorm and its severity. All of the data for surface and upper atmospheric levels were taken from ERA5 which is the ECMWF's 5th-generation global climate reanalysis; it provides global, hourly estimates of atmospheric variables, at a horizontal resolution of 31 km and 137 vertical levels from the surface to 0.01 hPa. Two types of data were used in this study, ERA5 hourly data on pressure levels from 1979 to present (gridded Reanalysis data of 0.25°x0.25° horizontal resolution)[25], and ERA5 hourly data on single levels from 1979 to present (gridded Reanalysis: 0.25°x0.25° (atmosphere))[26].

2.3 Fire Detection

Burned areas were detected using the data acquired from the Visible Infrared Imaging Radiometer Suite (VIIRS) 375 m thermal anomalies / active fire product from the VIIRS sensor aboard the joint NASA/NOAA Suomi National Polar-orbiting Partnership (Suomi NPP) and NOAA-20 satellites, in which its spatial resolution enhanced fire detection over small areas and at night time, see Schroeder W. et al (2014) for more details[27].

3.Results and Discussion

In mid-October 2019, Lebanon witnessed a series of destructive wildfires, in which it started on 13^{th} October in Chouf District and some other regions, and gradually the fires started and spreaded in many regions, and last till 17^{th} of October as shown in Figure 3.

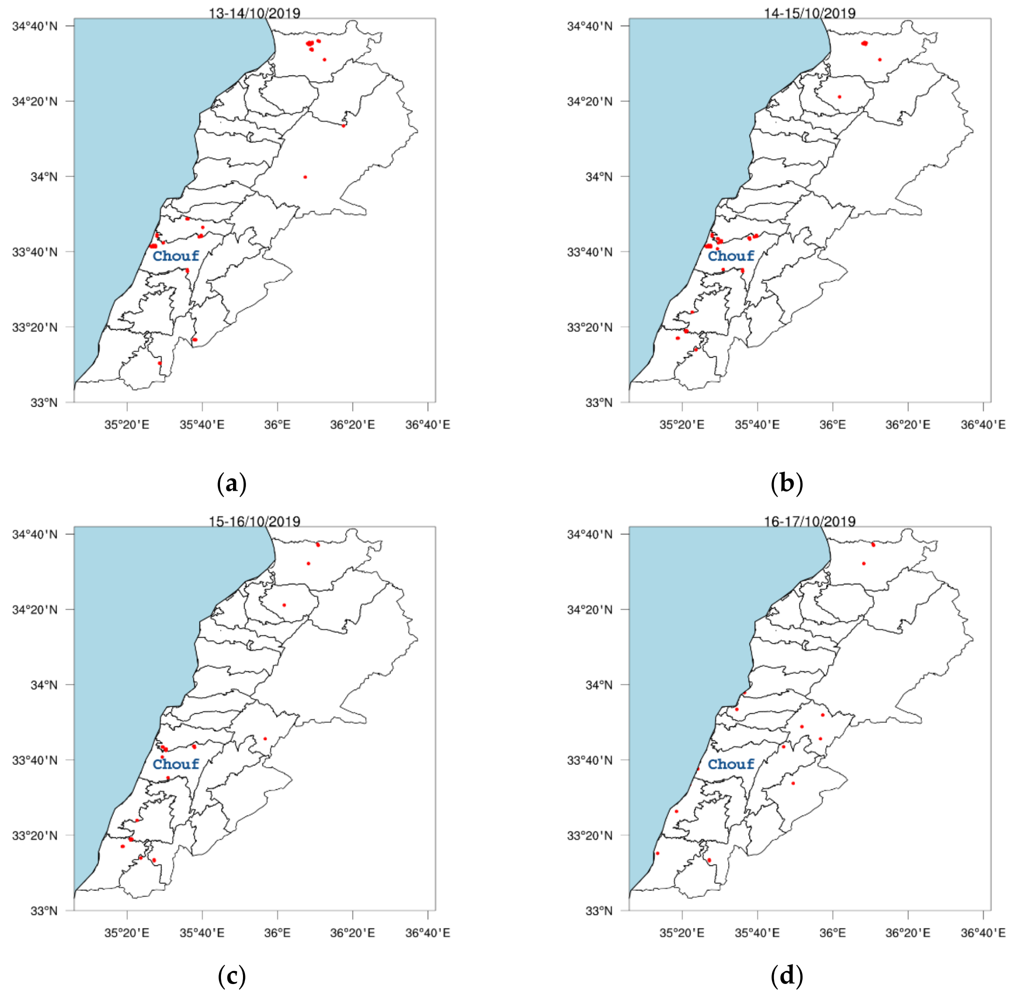
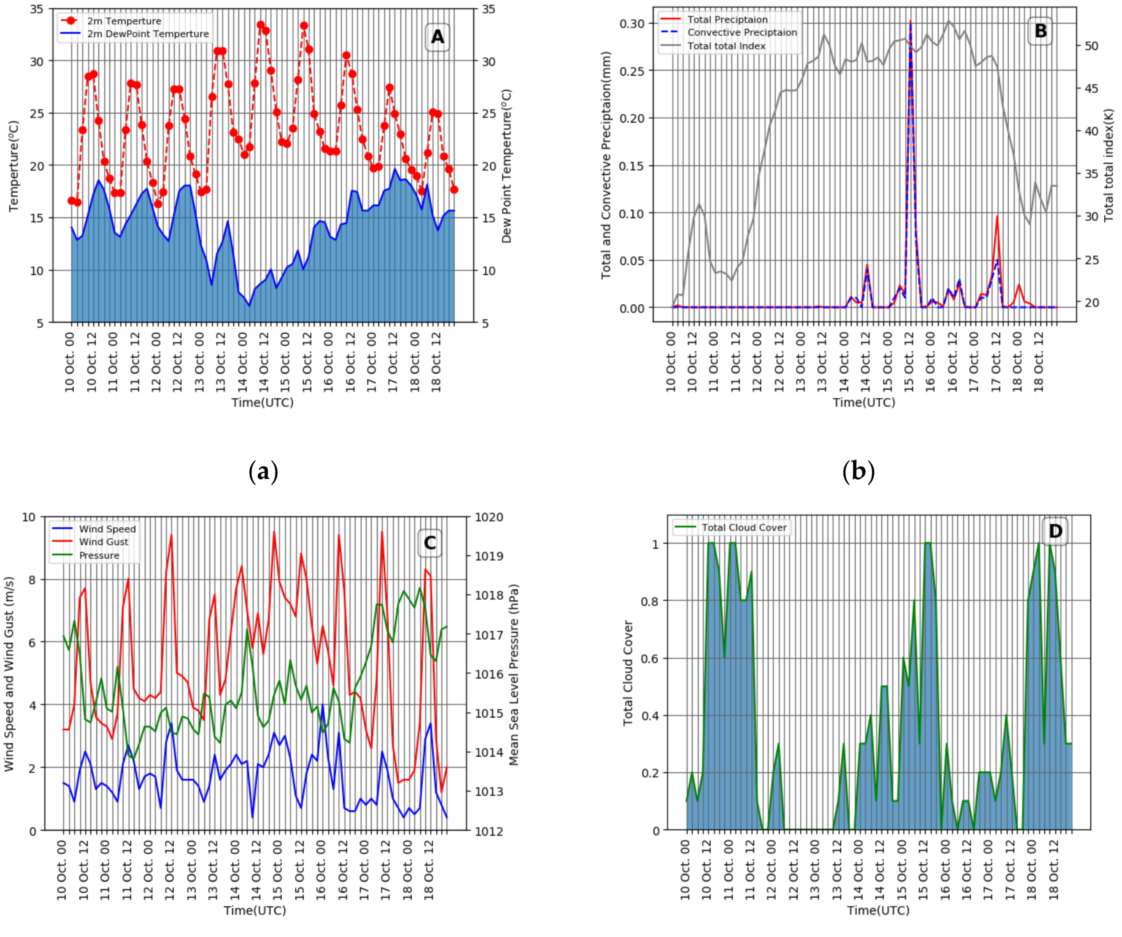


Figure 3. Burned areas in Lebanon on: (**a**) 13-14 October 2019; (**b**) 14-15 October 2019; (**c**) 15-16 October 2019 and (**d**) 16-17 October 2019.

Here, we are going to give a complete description about the atmospheric conditions preceding the wildfires occurrence:

1. Before days of the fire ignition (as seen since 10th October 2019 at 18 UTC), an upper cut off high blocking system built up over the Arabian Peninsula with a ridge extending towards the lands of the eastern Mediterranean; simultaneously, a pressure trough with an open wave which located over north-eastern Libya (about 22° E longitude) is progressing towards the east, in which this motion causes to deepen the open wave trough and distort long wave ridge as it will be seen later on, while at the surface there was a dominated high pressure system over the eastern Mediterranean, and a cold dry front has started to progress towards the eastern Mediterranean causing atmospheric instability (high values of total total index) and cloudy sky as shown in Figures (4),(5).
2. The progressive open wave with negative tilt moves towards the eastern Mediterranean on 11th October at 18 UTC, resulting in cold air advection and strengthening the surface high, building up the upper ridge with a notable extend in the cut off high. Lebanon is placed in the western side of the upper ridge with a dominant surface high pressure system (Figure (5)), the ridge aloft causes a subsidence of dry air (negative relative vorticity at 500 hPa and positive vertical velocity at 700 hPa) as shown in figures (7) and (8), in which this motion compresses the air in the lower atmosphere leading to warms it, simultaneously the rising heat from the earth surface will be trapped causing to heat the surface. The cold dry front is

passing the region in which Chouf region witnessed a lower temperature, cloudy sky with unstable conditions (higher values of total total index) and active gusty wind as shown in Figure (4).



(**a**) (**b**)

(**c**) (**d**)

Figure 4. Time series of some atmospheric parameters over Chouf district (33.7° N, 35.6°E) during 10-18 October 2019 including : (**a**) dew point temperature (orange contour lines) and temperature; (**b**) total precipitation, convective precipitation and total total index; (**c**) pressure, gust wind and wind speed and (**d**) total cloud cover.

3. The next day on 12th October at 18 UTC, the cold front has passed the region that witnessed a cooler temperature, slightly higher dew point temperature and mostly clear sky (Figures 4 and 5). While on the upper level, the trough has deepened and progressed rapidly to the east with a positive tilt, and the shortwave moved into the western side of the upper ridge causing to flattening it, meanwhile the surface high is still dominating over the region figure (5). This situation has led again in warmer, drier and unstable conditions in the next day due to air subsidence over the eastern Mediterranean (negative relative vorticity at 500 hPa and positive vertical velocity at 700 hPa) as shown in Figures (5), (7),(8).
4. On 13th October at 18 UTC, the deepen trough has continued its progressing towards eastern Mediterranean, and the upper ridge has built up again. Lebanon is placed in the transition zone between upper trough and upper ridge figure 5, in which it is represent a region of atmospheric instability due to strong wind aloft sinking to low levels producing (low level jet), and surface daytime heating simultaneously especially with clear sky figure (6), leading to activate the surface high with warmer and drier conditions, in which Chouf district witnessed a higher temperature and lower dew point as shown in figure (4). Moreover, with

the availability of mid-level moisture which is needed for convective clouds formation, thunder worked as the spark of the fire ignition in Chouf and dry fuels regions as shown in Figure (9).

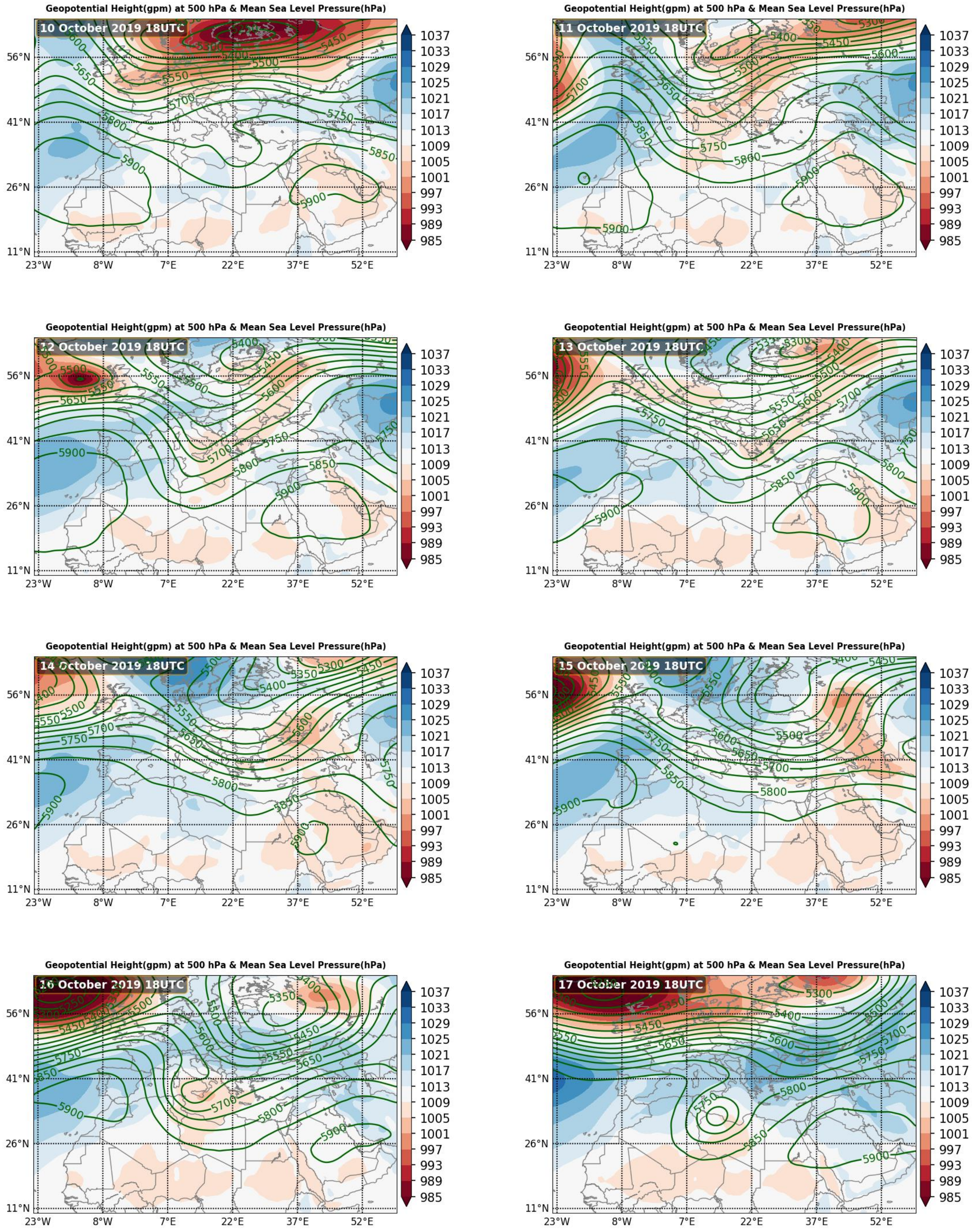


Figure 5. Geopotential height at 500 hPa (contour lines), and the MSLP (shaded)during 10-17 October 2019

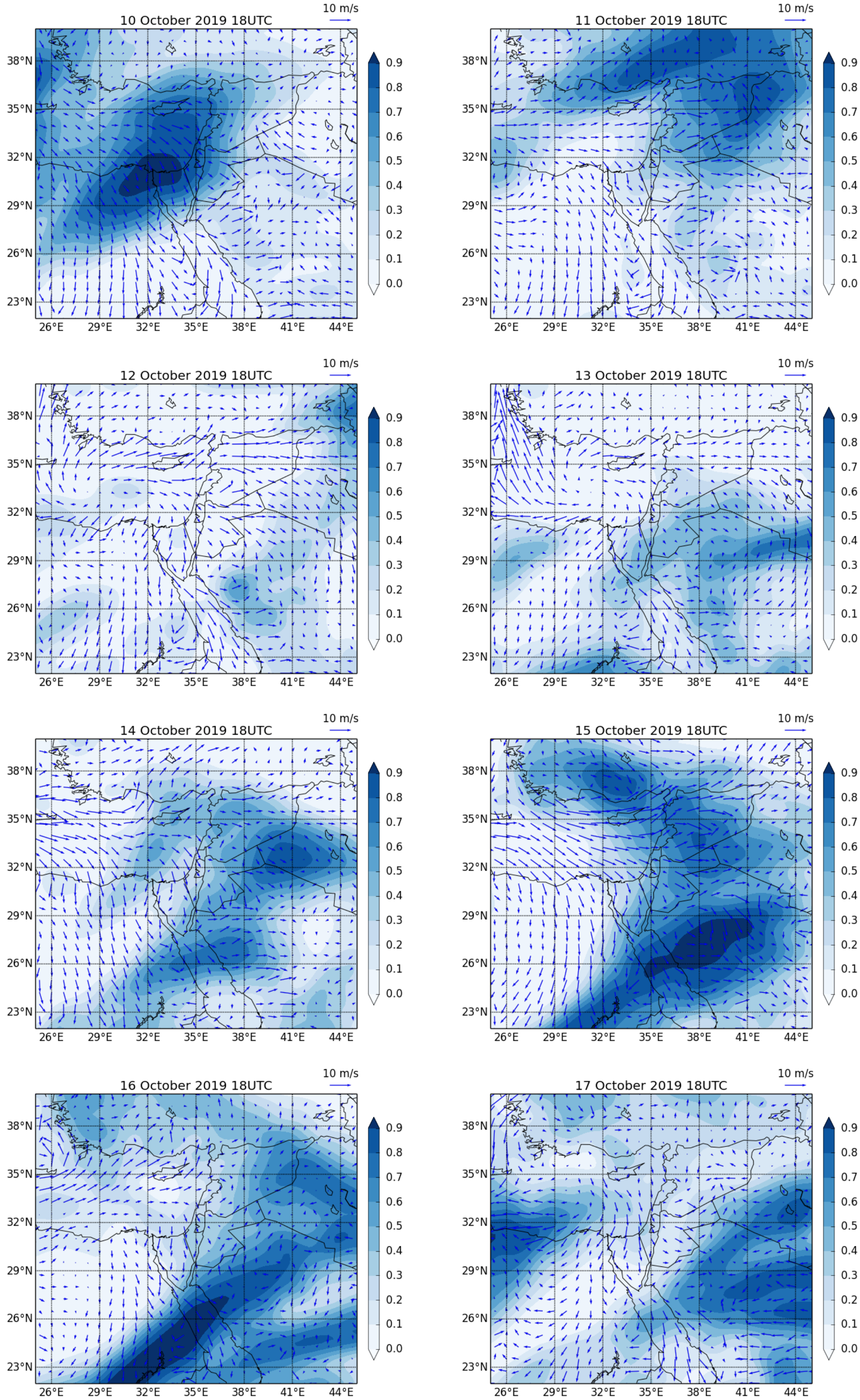


Figure 6. Total cloud(shaded), and surface wind during 10-17 October 2019

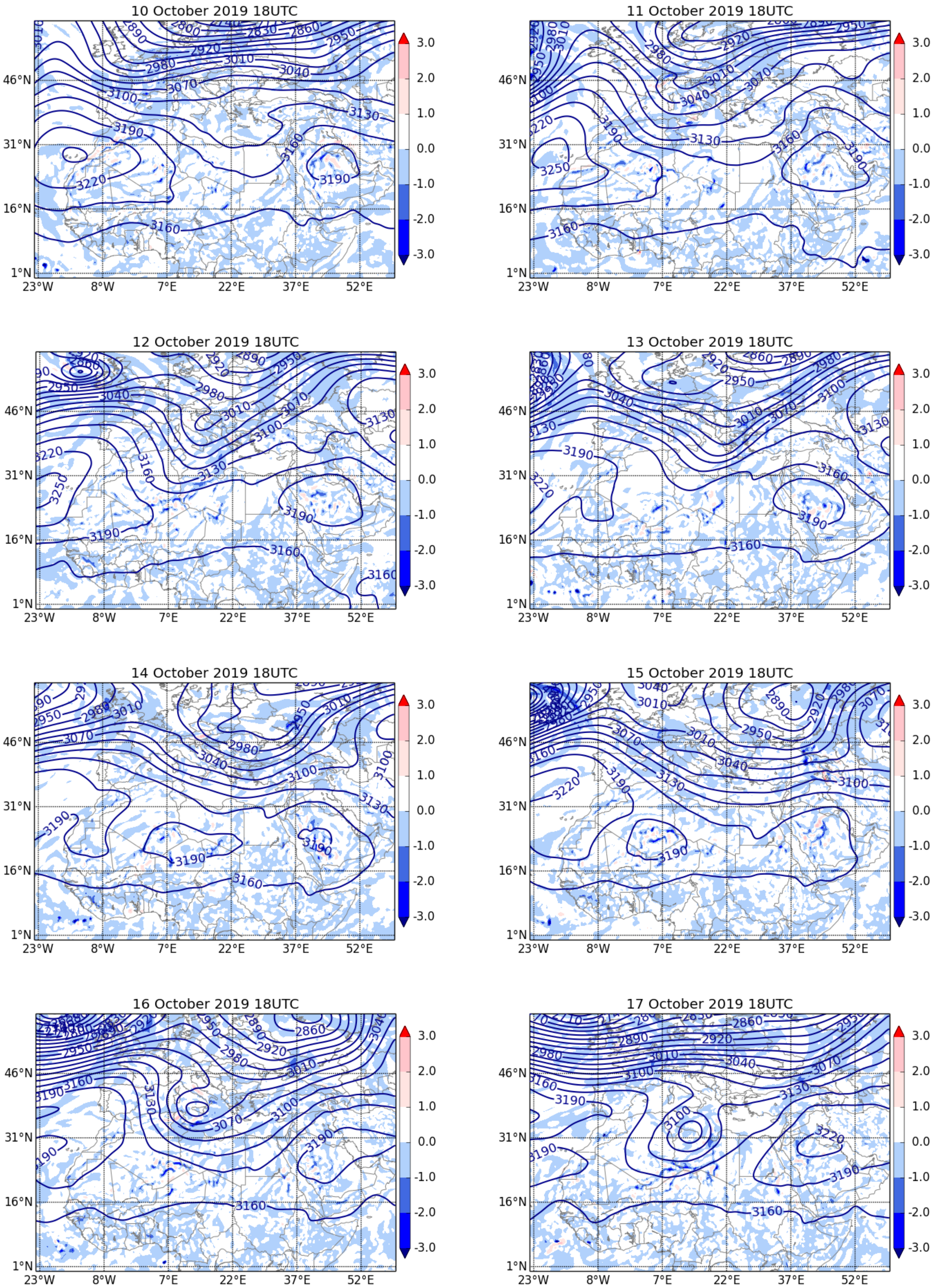


Figure 7. vertical velocity(shaded) and geopotential height at 700 hPa (contour lines) during 10-17 October 2019

5. On 14 October at 18 UTC, as seen in figure (5), both upper patterns and surface high has weakened, and thus surface Indian Monsoon have enhanced, and shifted towards the eastern Mediterranean. The surface heating has continued with lower dew point temperatures and unstable conditions (total total index reached more than 50 in Chouf) figure (4). This situation represents the breakdown of upper ridge leading to the advection of dry wind with high speed towards low levels producing (low level jet) associated with surface front, and with the available moisture in mid-levels as seen in figure(9), convective clouds has developed as explained before, producing thunderstorms with no rain over Chouf causing lightning that "we believe" it ignite fires (figure 3) in the dry fuels, and rapid fire has spread due to gusty surface winds in Chouf that witnessed temperatures higher than the averages. In addition to the role of wind in spreading the fires to farther regions, thunder clouds that formed over other regions due to the rising current that carried condensation nuclei (like ash) emitted from forest fires, can ignite new fires in other forest.

6. The situation on 15 October at 18 UTC has continued, because the upper flow is "Zonal", and as a result the weather at the surface remains warmer and drier than averages figure (5), where the rising hot air from forest fires reaching colder air at higher levels (with the available moisture) figure (9), leading to developing convective clouds producing thunderstorms and lightning with convective precipitation over Chouf of about 0.3 mm figure(4), and the number of affected regions of Chouf district has increased as shown in Figures 1.
7. Although Chouf district witnessed a rain fall in the previous day (figure 1), that help in firefighting, but fires have ignited again on 16 of October in many regions as seen in figure(1), due to the unstable and warm conditions associated to the upper ridge breakdown, in which the upper trough with positive tilt is moving towards the east, resulting in surface low retrogression, activating the surface high and leading to cold air advection figure(5), where Chouf region witnessed a lower temperature, with unstable conditions and active gusty wind trigging fire ignition as shown in Figures 4.
8. On 17th October at 18 UTC, the trough (open wave) has developed to a cut off low over the south western Mediterranean Sea, and the upper ridge over east Mediterranean Sea build up with a notable extend, while the high surface pressure strengthening, so Lebanon again will lie under blocking atmospheric system with continues warming, which forced the sea breeze towards the lands (cold front) due to the temperature gradient between land and sea surfaces as shown in figures (4) and (5). This situation resulted in convective clouds formation and less precipitation particularly in high terrain regions (ex. Chouf), and thus the fires continues in many regions, but the situation has become less critical as seen in figure (1).
9. Due to the previous situation, the heat wave has receded on 18th October, and fire ignition has stopped in Chouf district as shown in figure 1 and 5.

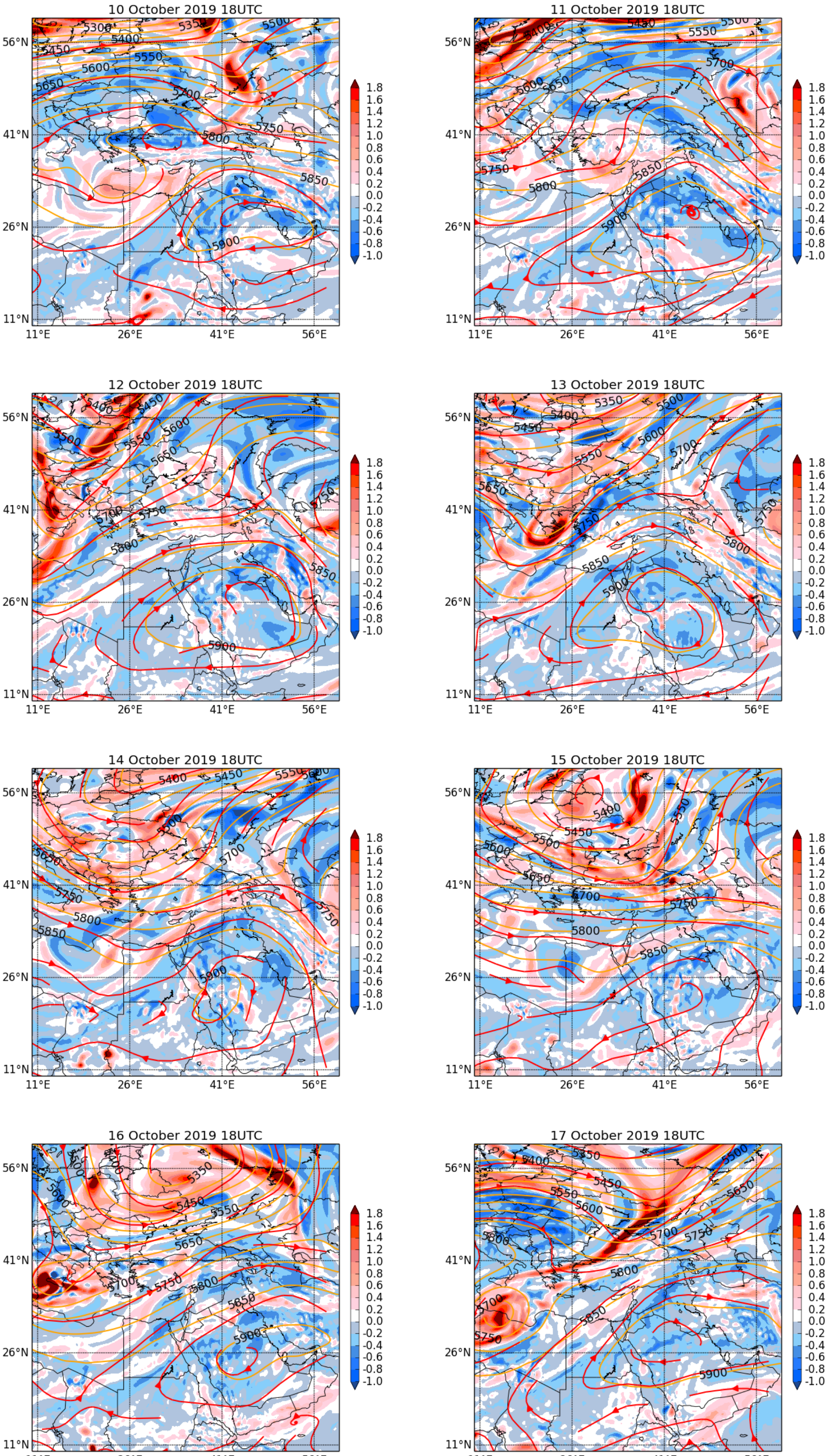


Figure 8. wind speed at 500 hPa (red contour line); geopotential height (orange contour line)and relative vorticity at 500 hPa (shaded)

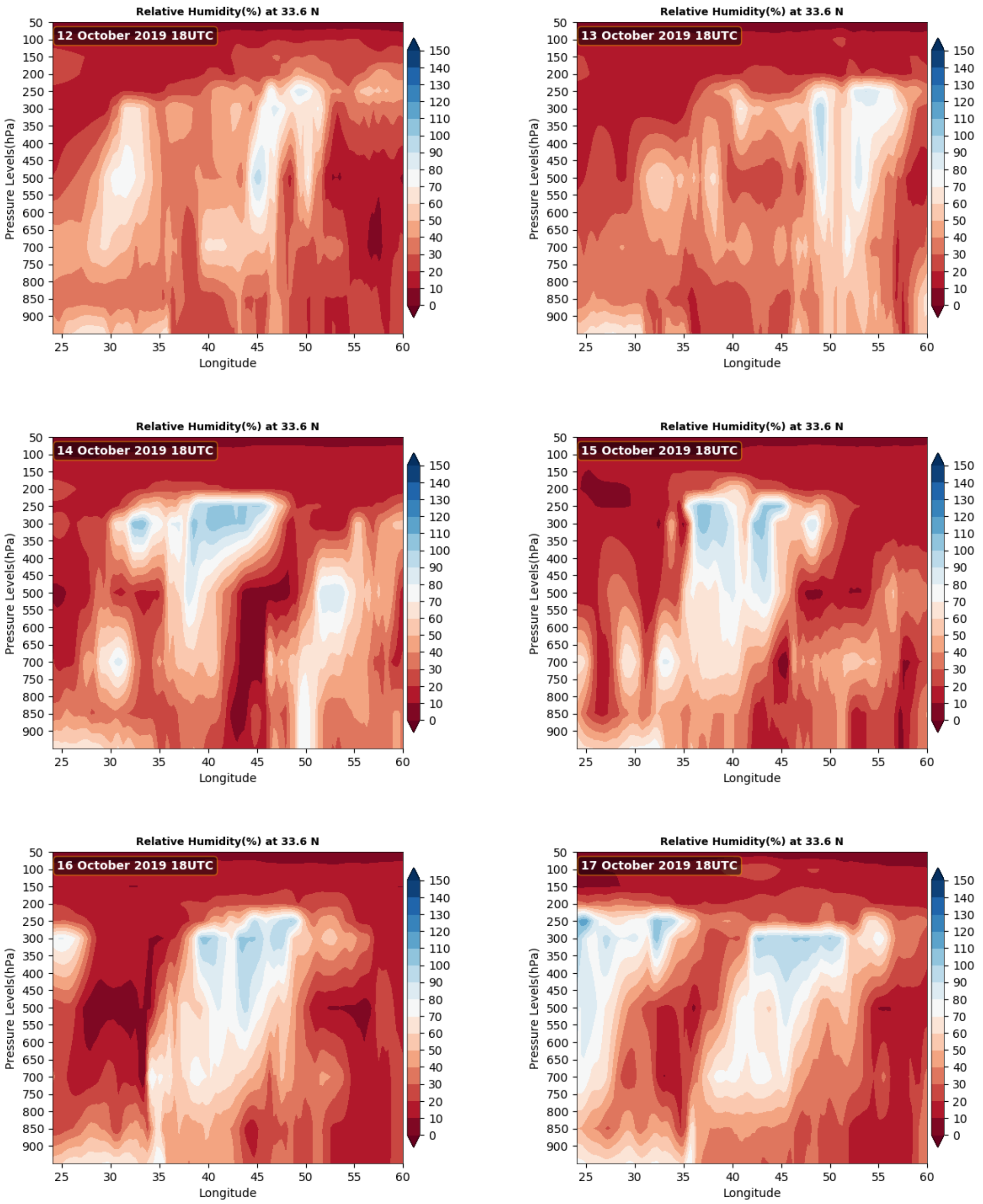


Figure 9. vertical cross section of relative humidity during 13-17 October 2019

4. Conclusions

In this study, it is found that the wildfire occurrence over Lebanon in mid-October 2019 is caused due to atmospheric situation represented by the domination of upper ridge and surface high pressure system leading to the formation of blocking, and resulting in heat wave over the eastern Mediterranean region due to adiabatic warming with sinking motion and warm air advection. On 13th to 14th October, the eastern movement of the upper open wave towards eastern Mediterranean caused the breakdown of upper ridge, in which Lebanon lied under transition zone between upper trough and ridge systems. The advection of dry air aloft to low level with cold front passage on the surface producing low level jet. The instability on the surface with the available moisture in mid-levels due to upper front leads to convective clouds producing thunderstorms with no rain (because of the lack in moisture on the surface) over Chouf district causing lightning, which is a critical tool to ignite fires in a rich area of dry fuels associated with low moisture and higher temperature and high wind speed. The period of fires has elongated till 18th October due to unstable and warm conditions associated to the upper ridge breakdown.

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Conflicts of Interest: The authors declare no conflict of interest.

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